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Authors(s)	Li, Chenfeng, Liu, Pengfei, Zhu, Xiao-Wei, Zhu, Anding
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A SIW-based Wideband Circularly Polarized 4×4 Patch Array Antenna in 45 GHz Band

Chenfeng Li¹, Pengfei Liu¹, Xiao-Wei Zhu¹, Anding Zhu²

¹State Key Laboratory of Millimeter Waves, Southeast University, Nanjing, P. R. China

²School of Electrical and Electronic Engineering, University College Dublin (UCD), Ireland
220160646@seu.edu.cn, xwzhu@seu.edu.cn

Abstract—In this paper, a substrate integrated waveguide (SIW)-based wideband circularly polarized (CP) 4×4 patch array antenna operating in 45 GHz band is proposed. Firstly, a series-fed 1×4 patch subarray is designed. Sequential rotation (SR) feeding technology is adopted to extend axial-ratio (AR) bandwidth. Then, a 4×4 patch array antenna using four 1×4 patch subarrays is presented. The anti-phase feeding network is used to obtain stable CP radiation patterns among wide frequency band. The proposed antenna was fabricated and measured. -10-dB |S₁₁| bandwidth of 27.6% (36.4-51.2 GHz), 3-dB AR bandwidth of 11.6% (41.6-47.6 GHz) and the peak gain of 17.1 dBic are achieved in the vicinity of 45 GHz.

Keywords—substrate integrated waveguide (SIW), circular polarization, 45 GHz, sequential rotation

I. INTRODUCTION

With the publication of IEEE 802.11aj-2018, the Chinese millimeter wave frequency band around 45 GHz has received more and more attention for future local area communication [1]. Research on wideband circularly polarized (CP) array antenna at 45 GHz is of great practical significance and engineering value.

Patch antenna is a kind of classic antenna due to its light weight and low profile. Truncating two corners of the radiation patch can generate CP radiation. In [2], a series-fed CP patch array antenna is presented by loading truncated patches on the slotted waveguide array. To decrease antenna profile, metallic waveguide can be replaced by substrate integrated waveguide (SIW) [3]. In [4], a compact SIW-based 4×4 patch array antenna is proposed. However, the 3-dB axial-ratio (AR) bandwidth is only 2.86%.

In this paper, a SIW-based wideband CP 4×4 patch array antenna is proposed. Sequential rotation (SR) feeding technology is adopted to expand AR bandwidth. Anti-phase feeding network is used to obtain stable radiation. In Section II, a series-fed 1×4 patch subarray is presented and analyzed. In section III, a 4×4 patch array antenna is described, fabricated and measured. Section IV is the conclusion.

II. PATCH SUBARRAY DESIGN

A. Patch Subarray Geometry

The 1×4 patch subarray is designed on the two-layer Taconic TLY-5 substrate ($\epsilon_r = 2.2$ and $\tan \delta = 0.0009$) and the thickness of each substrate is 0.254 mm. As shown in Fig. 1, the subarray includes four CP radiation patches (P_1 , P_2 , P_3 and P_4), which are fed by rectangular slots on the top side of SIW

transmission line. It can be seen that patch P_1 and patch P_2 are fed by longitudinal slot and transverse slot, respectively. The distance between patch P_1 and patch P_2 is $3/4\lambda_g$, where λ_g is the wavelength in SIW at 45 GHz. In this way, the SR feed is achieved in series-fed structure. Besides, the distance between patch P_2 and patch P_3 is $1/4\lambda_g$, which makes patch P_1 and patch P_3 have in-phase radiation. Fig. 2 shows the E-field distribution in SIW transmission line. The feeding phases of four radiation patches are 0° , 90° , 0° and 90° , respectively.

Fig 1. The geometry of 1×4 patch subarray. (a) side view, (b) top view. The parameter dimensions in millimeters are: $h_1 = 0.254$, $h_2 = 0.254$, $l_{p1} = 2.1$, $w_{p1} = 2$, $w_{n1} = 0.38$, $l_{s1} = 1.6$, $l_{p2} = 2$, $w_{p2} = 1.95$, $w_{n2} = 0.35$, $l_{s2} = 1.5$, $l_{p3} = 2.05$, $w_{p3} = 1.82$, $w_{n3} = 0.42$, $l_{s3} = 1.4$, $l_{p4} = 2.08$, $w_{p4} = 1.62$, $w_{n4} = 0.38$, $l_{s4} = 1.65$, $D_1 = 3.7$, $D_2 = 3.2$, $D_3 = 3.7$.

B. Patch Subarray Simulation

Ansoft HFSS 15.0 software is utilized to verify performance of the proposed antenna. Fig. 3 shows the simulated $|S_{11}|$, AR and gain of 1×4 patch subarray. It can be seen that the subarray has -10-dB $|S_{11}|$ bandwidth of 27.1% (38.5-51.1 GHz), 3-dB AR bandwidth of 11.1% (42.2-47.5 GHz) and peak gain of 12 dBic. The novel SR feeding structure introduces an extra minimum AR point and thereby expands the AR bandwidth.

The simulated radiation patterns of 1×4 patch subarray at 43 GHz, 45 GHz and 47 GHz are presented in Fig. 4. The main lobe at 45 GHz is stable along XOZ -plane and YOZ -plane. However, the main lobes at 43 GHz and 47 GHz offset about 10° along XOZ -plane. The phenomenon can be explained as the

sensitivity of distance between adjacent patches to radiation patterns among wide frequency band area.

Fig 2. The E-field distribution in SIW transmission line of 1×4 patch subarray.

Fig 3. The simulated $|S_{11}|$, AR and gain of 1×4 patch subarray.

Fig 4. The simulated radiation patterns at 43 GHz, 45 GHz and 47 GHz along: (a) XOZ-plane; (b) YOZ-plane.

Fig. 5 shows the surface current distribution of radiation patches in an excitation period. It appears that the instantaneous surface current directions on four radiation patches are almost the same. Besides, the rotational direction of surface current follows the right-hand rule when excitation phase changes successively from 0° to 270° . Thus, the 1×4 patch subarray can achieve the right-hand circularly polarized (RHCP) radiation.

Fig 5. The surface current distribution of radiation patches in an excitation period: (a) 0° , (b) 90° , (c) 180° , (d) 270° .

III. PATCH ARRAY DESIGN AND MEASUREMENT

A. Patch Array Geometry

Based on the 1×4 patch subarray presented in Section II, a 4×4 patch array antenna is furtherly designed. As shown in Fig. 6, the proposed 4×4 patch array antenna is composed of four 1×4 patch subarrays and a 1-4 SIW power divider. In order to obtain stable CP radiation patterns in wide frequency band, four subarrays are divided into two groups, which are fed in opposite directions.

Fig. 7(a) shows the geometry of SIW power divider. As can be seen, port 1 is input port and port 2-5 are output ports. To achieve impedance matching and uniform power distribution, the sizes and locations of specific metallic via-holes are optimized. To guarantee the maximum gain of 4×4 patch array antenna, the phases of four output signals received by port 2-5 should be 0° , 0° , 180° and 180° , respectively. The simulated results of S parameters in Fig. 7(b) indicate that in 43-47 GHz band, $|S_{11}|$ is lower than -20 dB, $|S_{21}| - |S_{41}|$ is lower than 0.6 dB, $\arg(S_{21}) - \arg(S_{41})$ is in 167° - 19° region. The amplitude and phase characteristics of S_{31} and S_{51} are similar to that of S_{21} and S_{41} .

Fig 6. The geometry of 4×4 patch array antenna. The parameter dimensions in millimeters are: $D_4 = 4.5$.

Fig 7. The SIW power divider: (a) geometry, (b) simulated S parameters. The parameter dimensions in millimeters are: $r_1 = 0.15$, $r_2 = 0.15$, $r_3 = 0.3$, $r_4 = 0.25$, $r_5 = 0.25$, $m_{x1} = 1.5$, $m_{x2} = 1.55$, $m_{x3} = 1.1$, $m_{y3} = 1.1$, $m_{x4} = 1$, $m_{y4} = 1$, $m_{x5} = 1.7$, $m_{y5} = 3.2$.

B. Patch Array Simulation and Measurement

The proposed 4×4 patch array antenna has been fabricated and the physical size is $4.4\lambda_0 \times 4.4\lambda_0 \times 0.076\lambda_0$, where λ_0 is the wavelength in free space at 45 GHz. Fig. 8 shows the simulated and measured $|S_{11}|$, AR and gain performances. The antenna has -10-dB $|S_{11}|$ bandwidth of 24.4% (37-50.5 GHz), 3-dB AR bandwidth of 12% (42.1-47.7 GHz), peak gain of 17.4 dBic in simulated results and -10-dB $|S_{11}|$ bandwidth of 27.6% (36.4-51.2 GHz), 3-dB AR bandwidth of 11.6% (41.6-47.6 GHz), peak gain of 17.1 dBic in measured results. It is obvious that the difference between simulated and measured results is small. Besides, the simulated results of 4×4 patch array in Fig. 8 does not change much compared to that of 1×4 patch subarray in Fig. 3 except for gain, which improves about 5.4 dB.

(a)

(b)

Fig 8. (a) Photo of the proposed array antenna and (b) the simulated and measured $|S_{11}|$, AR and gain of 4×4 patch array antenna.

The measured RHCP radiation patterns at 43 GHz, 45 GHz and 47 GHz are shown in Fig. 9. It can be observed that the main lobes are stable in all six patterns, which verifies the availability of adopted anti-phase feeding network. Besides, the side lobe levels are lower than -10 dB.

Table I listed the measured performance comparison with other wideband CP array antennas. The -10 dB $|S_{11}|$ bandwidth of the proposed antenna is the widest compared with that of the previously reported antennas operating in millimeter wave band.

TABLE I
COMPARISON BETWEEN DIFFERENT CP ARRAY ANTENNAS

Ref.	f_0 (GHz)	Size (λ_0^3)	-10-dB Imp. BW (%)	3-dB ARBW (%)	Max. gain (dBic)
[4]	35	$3 \times 4.5 \times 0.21$	5.7	2.86	15
[5]	25	$4.2 \times 4.2 \times 0.44$	8.7	18.9	18.2
[6]	60	$3.1 \times 3.1 \times 0.022$	13.3	15	17.5
This work	45	$4.4 \times 4.4 \times 0.076$	27.6	11.6	17.1

IV. CONCLUSION

In this paper, a SIW-based wideband circularly polarized 4×4 patch array antenna is proposed. A novel 1×4 patch subarray adopting sequential rotation feeding technology is designed to expand AR bandwidth. Besides, a compact SIW power divider using anti-phase feeding network is presented to obtain stable RHCP radiation pattern in wide frequency band. With the advantages of low profile, wide operating band and high gain, the proposed antenna is promising in future 45 GHz band wireless communication systems.

(a)

(b)

Fig. 9. The measured RHCP radiation patterns of 4×4 patch array antenna. (a) 43 GHz at XZ-plane and (b) YZ-plane, (c) 45 GHz at XZ-plane and (d) YZ-plane, (e) 47 GHz at XZ-plane and (f) YZ-plane.

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